

1 EFFECTS OF MANAGED BURNING IN COMPARISON TO VEGETATION CUTTING ON

2 DISSOLVED ORGANIC CARBON CONCENTRATIONS IN PEAT SOILS

3

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Abstract

9 Given continuing concern about rising concentrations of dissolved organic carbon
10 (DOC) in stream water leaving peat-covered catchments this study has
11 considered the impact of managed burning or cutting of *Calluna vulgaris*, a
12 dominant vegetation cover in many UK peatlands. The study considered pristine
13 mature *Calluna* stands in comparison to those that had been subject to cutting
14 and or managed burning up to 5 years after intervention. The study measured the
15 DOC concentration of both soil and surface runoff water over a period of 12
16 months in comparison to water table depth, conductivity and pH. The study has
17 shown that:

- 18 i) The depth to the water table decreases upon both burnt and cut sites
19 relative to controls in line with a change in evapotranspiration due to
20 loss of vegetation;

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21 ii) The DOC concentration of surface runoff water was not significantly
22 different ($p < 0.05$) between any of treatments and the control;

23 iii) The DOC concentration in soil water significantly ($p < 0.05$) decreased
24 with both burning and cutting but that these differences could be
25 explained by differences in water table and soil water conductivity.

26 The study suggests that declines in soil water DOC concentration are brought
27 about as different levels in the peat profile become the dominant source as due
28 to changes in water table brought about by changes in evapotranspiration that
29 result from the loss of vegetation. The changes in water table mean that and that
30 this mechanism may explain other observations of DOC concentration change
31 with management. Cutting and burning may represent a management
32 intervention that could be effective at reversing the current trends in DOC
33 transfers from peat-covered catchments.

34

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INTRODUCTION

36 Increasing concentrations of dissolved organic carbon (DOC) have been
37 observed in Boreal and sub-Boreal regions across the Northern hemisphere.
38 Increases have been observed in North America (Driscoll et al., 2003) and in
39 Central Europe (Hejzlar et al., 2003). For the UK, Worrall and Burt (2007a) have
40 shown that out of 315 catchments studied in the UK, 68% showed a significant
41 increase over timescales of between 9 and 42 years, for catchment areas
42 ranging between 400 m² and 9800 km². These increases have generally been
43 associated with peat soils (Aitkenhead et al., 1999). Increases are not, however,

44 universal. Skjelkvale et al. (2001) report a mixed picture for lakes in Finland,
45 Norway and Sweden. Equally, although Worrall and Burt (2007b) have shown
46 widespread increases in DOC flux from peat-covered catchments in the UK, they
47 have also shown significant decreases in DOC flux from all the peatlands of
48 south western England.

49 Increasing concentrations of DOC entering surface water is a cause of
50 concern because it could be indicative of increasing losses of carbon from the
51 vital peatland carbon stores. Furthermore, the concentration of DOC is a major
52 problem for water companies in the UK and parts of Northern Europe, as the
53 removal of DOC from water supplies is one of the greatest costs in the treatment
54 process. Incomplete removal of DOC leads to coloured water which is of low
55 aesthetic quality; it increases the potential for biological contamination by
56 consuming free residual chlorine; and can form potentially carcinogenic tri-
57 halomethanes whose concentration in drinking water is limited by law in the UK
58 (Hsu et al., 2001).

59 There are several proposed mechanisms to explain the observed
60 increases in DOC. These include: increasing air temperature (Freeman et al.,
61 2001a); changes in pH (Krug and Frink 1983, Lofts et al. 2001); change in the
62 amount and timing of rainfall causing shifts in the balance of flowpaths (Tranvik
63 and Jansson, 2002); increases in atmospheric CO₂ concentration (Freeman et
64 al., 2004); changes in atmospheric deposition particularly of S (Evans et al.,
65 2005); occurrence of severe drought (Worrall and Burt, 2004); eutrophication
66 (Harriman et al., 1998) and these could be enhanced by local land management

67 (e.g. Mitchell and McDonald, 1995). It is likely that some or all of these drivers
68 have contributed to increases in DOC concentrations.

69 Given the consequences of increased losses of DOC from peat soils for
70 carbon storage and water treatment is it possible to manage these changes? It is
71 unlikely that the effects of climate change or atmospheric deposition can be
72 reduced on short timescales (<10s yrs). It would therefore seem prudent to
73 manage these vulnerable environments in order to minimise DOC losses through
74 appropriate land use. Unlike many Boreal and sub-Boreal peatlands the peat
75 soils of the UK uplands are heavily and extensively managed for livestock and
76 recreational shooting. In order to increase productivity managed burning of
77 vegetation has been a common feature of the UK uplands. Up to 40% of English
78 moorland has been burnt with approximately 20% of upland heath and bog in the
79 North Pennines Area of Outstanding Natural Beauty (AONB) having been burnt
80 within the past 7 years (Yallop et al. 2006). Burning is regulated by the UK
81 Department for Environment, Food and Rural Affairs (DEFRA). DEFRA
82 recommends (DEFRA, 2007) that individual burns should; not exceed 2 hectares
83 with a maximum width no greater than 30m (DEFRA, 2007); burning that is no
84 more frequent than once every 12 years; and finally, that burning takes place
85 between 1st October and 15th April. The aim in restricting the period when
86 prescribed burning can take place is to ensure a 'cool' burn by not allowing the
87 burning of peat and vegetation during drier, hotter summer months. A 'cool' burn
88 aims to remove the vegetation layer without damaging the underlying litter or
89 peat.

90 The vegetation response to burning is well documented (Mallik and
91 Gimingham 1983; Hobbs 1984; Hobbs and Gimingham 1984). The burning of
92 peatland vegetation promotes the development of grass-dominated communities
93 especially on shorter burning rotations (Hobbs 1984). This vegetation response
94 improves grazing for sheep and is reflected in higher sheep performance on
95 burnt plots (Lance 1983). Grouse production has also been correlated with the
96 density of burnt areas (Picozzi 1968). Clay et al. (2010) estimated the total C
97 budget of plots under a range of burn managements including unburnt controls
98 and showed that while the total C budget on unburnt plots was a source of 156.7
99 $\text{gC m}^{-2} \text{yr}^{-1}$ that on burnt plots was total C source was $117.8 \text{ gC m}^{-2} \text{yr}^{-1}$, i.e. the
100 study showed that although all plots were net sources of C the burnt plots
101 represented an avoided loss. What, however, are the consequences of managed
102 burning for water quality and especially for DOC?

103 At the plot scale, Ward et al. (2007) and Clay et al. (2009a) found no
104 significant difference in DOC concentrations in soil waters between burnt and
105 unburnt sites while Worrall et al. (2007) and Helliwell et al. (2010) showed a
106 significant decrease in DOC concentration in soil water on burnt sites, though the
107 latter study was not on a deep peat. Worrall et al. (2007) and Ward et al. (2007)
108 considered the same site and only considered burnt sites 9-10 years after a burn.
109 Clay et al. (2009a) and Helliwell et al. (2010) consider changes after a burn and
110 Clay et al. (2009a) considered pre-burn vs. post-burn. Clay et al. (2009a) is the
111 only study to consider concentrations in surface runoff at the plot scale, and
112 found no significant difference between burnt and unburnt plots, and none of

113 these studies considered stream water DOC concentrations in comparison to
114 measured soil or surface runoff water.

115 There are also a number of studies at larger scales i.e. catchment scale.
116 Burns more than 4 yrs old, or those on soil types other than blanket peat, show
117 no observed effect on humic DOC in catchment drainage (Yallop et al.,
118 2008; Yallop & Clutterbuck, 2009; Chapman et al., 2010). In total or partly
119 blanket peat catchments, however, Yallop et al. (2008) and Yallop and
120 Clutterbuck (2009) found a significant positive relationship between the area of
121 new burn (typically <4 yrs old) on blanket peat and drainage humic DOC
122 concentration. Using long-term trend analysis, Clutterbuck & Yallop (2010)
123 showed that this relationship explains a much greater fraction of the increase in
124 drainage DOC over the recent past than either increasing temperatures or
125 declines in acid deposition. Yallop et al. (2010) showed that increases in humic
126 DOC concentrations related to new moorland burns on blanket peat represent an
127 increase in loss of carbon, and that areas of new burn (<4 yrs old) on blanket
128 peat show a 5- to 15-fold greater loss of humic DOC compared to areas not
129 burned that recently.] However, Chapman et al. (2010) also note increases in
130 DOC concentration in a range of peat-covered, English catchments, including
131 ones where there was burn management, but observed changes were
132 independent of burning and the variation in increase was larger than that
133 observed by Clutterbuck and Yallop (2010), rather magnitude of increase in DOC
134 concentration was greatest in catchments where DOC concentration had been
135 lowest at the start of the period of observation. However, the study of Chapman

Comment [F1]: Gareth – can you advise
– what it be more accurate to say these
studies considered colour?

136 et al. (2010) has recently been debated by both Yallop et al. (2012) and
137 Chapman et al. (2012).

138 If the evidence of the effect of burning upon DOC concentration is still
139 debated there is evidence that burning can be detrimental in other ways.
140 Wildfires, accidental burns, have been linked to increased peat erosion (Tallis,
141 1997), also managed burns that get out of control can burn larger areas of
142 vegetation than required. Both can lead to a loss of ecosystem production
143 negating any potential gains had the vegetation been left alone. Moreover, out of
144 control burns can burn into the litter layer and the underlying soil thus releasing
145 carbon that was in long-term storage. Given the potential detrimental effects of
146 burning alternative means of controlling vegetation have been sought. This study,
147 therefore, set out to compare the impact of managed burning over time with the
148 alternative practice of heather cutting to contrast their impacts on peatland
149 hydrology and carbon storage.

150

151 **APPROACH AND METHODOLOGY**

152 ***Study sites***

153 The study sites were all situated in the Goyt Valley, Derbyshire, England, an area
154 within the Peak District National Park (Figure 1). The area is a water supply
155 catchment for the city of Manchester and is entirely owned by the local water
156 company. The soils of the valley are dominated by peats and as a consequence
157 rising DOC concentrations are the dominant water quality problem for this supply
158 although there is no long period observations to suggest a trend in water colour

159 or DOC. The peat soils are dominated by *Calluna vulgaris* with some *Sphagnum*
160 *spp.* mosses in wetter areas. The area is used for sheep grazing but this is light
161 and largely away from the peat soils and wetter patches. The valley has been
162 used for recreational grouse shooting but there has been no managed burning
163 within the catchment for at least 5 years, although an accidental burn occurred in
164 the valley in April 2007.

165 The experiment is designed to compare the cutting of *Calluna vulgaris* as
166 an alternative to burning this vegetation type. The cutting of *Calluna vulgaris* was
167 performed in two ways: cut and lift; and cut and leave. In both cases the
168 vegetation is flailed to the ground level but in the former case the cuttings are
169 removed from the site with a forage harvester while in the latter the cuttings are
170 left as they fall.

171 The sites available to the study included: a fresh cut and leave (GS1); a 1-
172 year old cut and leave (MOSS); a 1-year old cut and lift (BEN and GS3); a fresh
173 burn (ob); a 1 year old burn (BN and BS); a 5 year old burn (PROM) and a
174 control (PAT). The control site is typified by mature to degenerate *Calluna*
175 *vulgaris* with an open structure allowing mosses and lichens to develop. The 1
176 year old burn treatment was part of an accidental fire that occurred on April 2007.
177 Within the scar of this accidental burn sites were chosen where ground
178 conditions mimicked those of managed burns, i.e. litter still present and no sign of
179 soil scorching, and therefore, the 1 year old burn was taken as equivalent to a
180 managed burn – details are given in Table 1.

181 Before the start of the experimental burns of *Calluna sp.* were conducted
182 in April 2008. This was beyond the season permitted in the DEFRA Burning Code
183 but the burns were permitted by license of Natural England for our research: two
184 fresh, or new burns were conducted upon the study site. The burning was
185 conducted by local estate staff trained and experienced in conducting managed
186 burns of *Calluna sp.* The treatments were then instrumented as soon after the
187 burns as possible and allowed to settle such that sampling could begin in May
188 2008. Subsequently sampling took place every month until June 2009.

189 All the plots were chosen to be in deep peat, i.e. peat of greater than 50
190 cm deep (Avery, 1980). The size of all plots, except those designated as controls,
191 was consistent with the typical size of prescribed burn plots as set out within the
192 Defra burning code (2007), ie. No more than 150m long by 30m wide. The
193 management plots were sited along a flat ridge of peat which meant that no plot
194 was positioned hydrologically above any other or indeed below another
195 management.

196

197 ***Monitoring regime***

198 The sites chosen for their particular management were set up so that within each
199 treatment there were duplicated plots and within each plot sampling for soil water
200 and runoff water was triplicated. In some cases the duplicated plots are within the
201 same site but this was not always possible. For example, sites BS and BN are
202 both old burn (1 year) treatments but it was not reasonable for them to be on the
203 same site, and so these plots were placed on different sites of the same

204 treatment (Table 1). Soil water from below the water table was accessed via a
205 series of dipwells from the surface. In each plot three dipwells were placed to at
206 least 90 cm depth with openings along the entire length. Depth to water table and
207 soil water was measured at least once a month.

208 In addition to the soil water samples, crest-fall runoff traps were installed
209 alongside each dipwell in order to intercept surface flow from the plots. These 20
210 cm deep by 5 cm diameter upvc pipes were sunk into the peat surface with seals
211 at both ends but with holes at the surface to allow in any surface runoff, holes
212 were aligned with and perpendicular to the local slope. Traps were inspected at
213 least once a month until June 2009 and if water was present it was sampled. The
214 samples were then analysed using the same techniques as for the soil water
215 samples collected from the dipwells. The actual runoff from a plot and a hillside to
216 a catchment will be a mixture of the soil and runoff water compositions sampled
217 by the installed equipment – the implications of the mix of the sampled waters are
218 discussed below.

219 Water samples from the dipwells were analysed for pH, conductivity,
220 absorbance at 400nm (Abs_{400}), E4/E6 ratio and DOC concentration. Absorbance
221 was measured at 400 nm for a basic colour reading (Thurman 1985). DOC
222 concentrations were measured colorimetrically using the method by Bartlett and
223 Ross (1988). By measuring both absorbance at 400 nm and DOC, specific
224 absorbance can be evaluated and thus the nature of the DOC can be tested.
225 Furthermore, the E4/E6 ratio (the ratio of absorbance at 465 nm to absorbance at
226 665 nm) was also measured as an additional assessment of DOC composition.

227 Chen et al. (1977) has shown that the E4/E6 ratio is: (i) mainly governed by the
228 particle size or molecular weight; and is affected by pH: pH of all water samples
229 was included as a covariate in the analysis. The pH and conductivity were
230 measured by electrode methods.

231 In total the study consisted of 63 dipwells and 63 runoff traps which over
232 the time of the study meant that there was a possible 773 possible observations
233 of each determinand considered in both soil and runoff water. However, due to
234 low water tables it was not always possible to sample soil or runoff water on
235 every occasion.

236

237 ***Statistical Methodology***

238 The sampling survey design used in this study is not a complete factorial with
239 respect to all the factors that could be considered. However, within this design it
240 is possible to consider the statistical significance of the following factors:

241 *Treatment* – these are the differences between the cutting and burning
242 treatments which at its maximum had the following levels at the study
243 location. Therefore, as an additional analysis and in order to test whether burning
244 treatments are distinctly different from cutting treatments the treatment levels
245 were amalgamated to just 3: control, cut and burnt.

246 *Month* – in order to allow for the difference between sampling days and in order
247 to assess the seasonal cycle the month in the calendar year is included as a
248 factor where: January = 1 and December = 12.

249 *Runoff vs. surface water* - the analysis was performed for all measured soil water
250 components (based on samples collected from dipwells) and then separately for
251 the individual measured components in the runoff water samples (samples
252 collected from the runoff traps). However, in separate analysis the soil water and
253 runoff water samples were compared in order to test the significant differences
254 between the two flowpaths across the year and across the treatments.

255 Appropriate covariate information was used. The magnitude of the effects of
256 each significant factor and interaction were calculated using the method of Winer
257 (1971). Post-hoc testing of the results was performed for pairwise comparisons
258 between factor levels using the Tukey test in order to assess where significant
259 differences lay between factor levels. There are several problems associated with
260 using the general linear modelling approach. Firstly, the Levene test was used to
261 assess the homogeneity of variance with respect to all factors in the general
262 linear model. If a set of data failed the Levene test the data were log-normalised
263 and re-tested for normality – in the case of this study no further transformations
264 proved necessary. Secondly, all significant differences are assessed at the 95%
265 probability of not being zero. Thirdly, the ANOVA should have sufficient statistical
266 power in order not to risk type II errors at a given level of significance: the survey
267 design used in this study was that shown to be effective in Worrall et al. (2007).
268 Fourthly, each plot had a unique treatment (eg. burnt) and no additional
269 treatments were applied to any individual plot within the study period and so a
270 repeated measures design was not required.

271

RESULTS

272

273 *Depth to water table*

274 The depth to the water table was measured 437 times. The average depth to the
275 water table on the control site was 44 cm below the surface but on the new cut &
276 leave site the median depth to the water table was 6 cm (Fig. 2) and although
277 each treatment was measured at least 56 times across each month of the year
278 the new cut & leave treatment has a far more restricted range than the control.
279 When comparing all the treatments the difference between them is significant
280 and is the most important factor in the ANOVA (Table 2). The post hoc
281 comparison shows that there is a significant difference between the control and
282 all treatments except with the new burn. In all cases, except that of the new burn
283 treatment, the depth to the water table decreases with treatment. When the data
284 are amalgamated the importance of the difference between treatments increases
285 and post hoc testing shows significant differences between burning and cutting
286 and the controls. The effect of management intervention be it cutting or burning
287 can be explained as the loss of vegetation causes a decrease in
288 evapotranspiration that means water tables can rise. The significant difference
289 between burning and cutting treatments may be explained by a mulching effect of
290 the cut vegetation left upon the soil surface, however, it should be noted that
291 there was no significant difference between the cut and leave treatments and the
292 cut and lift treatments, and thus an alternative explanation of the difference may
293 be due to changes in aerodynamic roughness and surface resistance

294

295 **Soil water DOC**

296 Soil water DOC was measured in 309 samples with no treatment measured less
297 than 21 times. The median DOC concentration for the control was 142 mg C/l
298 while for the new cut & leave the median value was 96 mg C/l (Fig. 3). The first
299 ANOVA between all treatments shows a significant difference between
300 treatments although it was less important than the month factor or the error term
301 (Table 2). The post hoc analysis shows that the only treatment that is different
302 from the control is the new cut and leave. There were no significant differences
303 between the new burn and any other treatment, but the new cut and leave was
304 significantly different from the 1 year old burn; old cut and leave; and the new cut
305 and lift.

306 When data are amalgamated the difference between treatments explains
307 only 5% of the variation in the original dataset. The difference observed is
308 between the control and the cut treatments with the average DOC concentration
309 on cuts being 24% lower, though it should be noted that the average DOC
310 concentration for burn treatments was also 22% lower on average but the
311 difference was not significant at the 95% probability.

312 When covariates are included the difference between treatments becomes
313 insignificant, the two covariates that are found to be significant at least at the
314 95% probability, and explain the differences previously observed between
315 treatments are the log of the depth to the water table and the conductivity of the
316 soil water samples. The DOC concentration of soil water samples rose with
317 increasing depth to the water table and with increasing soil water conductivity.

318

319 ***Soil water DOC composition***

320 The E4/E6 showed a significant difference between treatments but the post hoc
321 analysis showed that the significant differences were between all sites, including
322 the control, and two, but not all three of the burn sites (Fig. 4, Table 2). The new
323 burn and 5 year old burn were significantly different from all the other sites and in
324 both cases were significantly lower. This view is confirmed when the data were
325 amalgamated and there was a significant difference between the control and the
326 burnt sites but not between the cut sites and the control, however, on average
327 the E4/E6 ratio was lower on the cut sites. No covariates were found to be
328 significant. Therefore, E4/E6 tends to be lower on burnt sites implying that higher
329 molecular weight and more humified DOC being present (Chen et al., 1997).

330 The specific absorbance was significantly different between treatments
331 (Fig. 5, Table 2) but the difference explains only 10% of the original variance and
332 the pattern of post hoc differences suggests the specific absorbance is following
333 DOC concentration with only the new cut and leave being significantly different
334 from the control and it having a higher specific absorbance than the control.
335 Again when the data are amalgamated there is a significant difference between
336 control and cut sites but not between burnt and cut sites. Moreover the control
337 site has the lowest specific absorbance which is in line with its higher DOC
338 concentration. When covariates are included the log of soil water conductivity is
339 found to be significant and inclusion of the covariates does negate any significant
340 difference between the control and the new cut and leave site. This behaves

341 similarly to differences in the DOC concentration implying that specific
342 absorbance decreases with increasing DOC concentration and does not suggest
343 any compositional differences between treatments with respect to specific
344 absorbance.

345

346 ***Surface runoff water DOC***

347 The DOC of the surface runoff could be measured in 108 cases (Fig. 6, Table 2)
348 with the control being the least represented with 11 samples. There is a
349 significant difference between treatments with respect to the surface runoff DOC
350 concentration but the post hoc analysis shows that no significant differences exist
351 between the control and any of the cut or burnt sites. The significant differences
352 that do exist are between the 5 year old burn and the old cut and leave; and the
353 other burnt and cut sites, but not with the control site. When the data are
354 amalgamated then neither factor is significant, i.e. there is no general difference
355 between burnt or cut sites and the control.

356 Depth to the water table could not be included as a covariate as the
357 measurement is made on the day of sampling and would not relate to conditions
358 generating the surface runoff. Therefore, only the pH and the conductivity of the
359 surface runoff samples can be used as covariates. Both pH and conductivity are
360 significant and both show a positive correlation with surface runoff DOC
361 concentration. The relationship with pH and conductivity can be interpreted in
362 terms of the source of the surface runoff.

363

364 **Comparison of surface runoff and soil water**

365 The comparison of the surface runoff and soil water DOC concentrations show
366 that there was a significant difference between sources independent of difference
367 between treatments and the difference between months (Table 2). In this case
368 the soil water DOC was on average 69% of the surface runoff DOC
369 concentration. There was a significant interaction between the type and the
370 month of sampling, i.e. the difference between surface runoff and soil water
371 varies across the year. In fact there were only 5 months where there was a
372 difference between surface runoff and soil water DOC concentration but in 7
373 months there was no difference, in particular there was no difference in the
374 summer months.

375 For the DOC composition there was no significant difference between
376 surface runoff and soil water in terms of specific absorbance (Table 2) but there
377 was a significant interaction between type and month. Upon examination this was
378 found to be due to large values of specific absorbance for surface runoff
379 concentrations in September. However for E4/E6 there was a significant
380 difference between types (Table 2) and the E4/E6 was lower in the surface runoff
381 compared to the soil water and there was a significant interaction but it was
382 between the type and treatment factors and not with the month factor. For most
383 treatments the soil water E4/E6 was greater than the surface runoff E4/E6 but for
384 the new burn this was reversed.

385

386 ***Frequency of surface runoff***

387 The proportion of times that surface runoff was detected upon each site was
388 given in Table 3. The values of proportion of detection vary from 10% upto 46%.
389 It was possible to perform a significance test between these measured
390 proportions using the approach of Clay et al. (2009b). This significance test does
391 imply that there is a significant increase in proportion of surface runoff where
392 there had been management intervention with an approximate doubling of runoff
393 frequency. Such a test could readily be distorted by the nature of each plot, i.e.
394 the slope of one plot under the treatment being different from the slope of
395 another, but this is less true if the comparison is made between management
396 type and in which case there is a significant difference between managed sites
397 (burnt and cut) and control sites. Although there was only a limited number of
398 sites there is no significant correlation ($p > 0.05$) between proportion of surface
399 runoff and the average DOC concentration of the surface runoff at that site, this
400 supports the results of the ANOVA that there was no management effect upon
401 surface runoff DOC concentration.

402

403

DISCUSSION

404 The study has shown a significant effect of cutting and of burning upon soil but
405 not surface runoff water DOC concentrations, why does this occur? There are
406 several lines of evidence from the study that need to be explained. Firstly, there
407 was a decrease in soil water DOC concentrations but not in surface runoff water
408 concentrations; the effect was present for both burning and cutting treatments
409 relative to the control; and the effect decreases or disappears when covariates

410 were included with the proportion of variance explained by the treatment factor
411 decreasing without a decrease in the unexplained variance, i.e. the differences in
412 DOC observed were due in part to differences in the depth to the water table and
413 differences in electrical conductivity of the collected soil water samples. A
414 possible explanation of the observed differences in soil water DOC is that the
415 observed changes were being driven by changes in water table driven by loss of
416 vegetation. The change in the average water table position between control and
417 cut or burnt sites was at least a rise of 8 cm but was 31 cm for cut sites. If the
418 DOC concentration in soil water decreases towards the surface then as the
419 average position of the water table rises it is accessing a lower concentration
420 source of DOC. This view is supported by the fact that surface runoff
421 concentrations of DOC are significantly lower than soil water concentrations, i.e.
422 soil water becomes more like surface runoff as it becomes shallower thus the
423 concentration of DOC drops. This may not only mean that the surface layers of
424 peat are not good sources of DOC but also that higher in the soil profile the water
425 is more likely to be mixed with rainwater and rainwater has a very low DOC
426 concentration – reported ranges of DOC concentration in rainwater vary from
427 0.82 – 2 mg C/l (Dawson and Smith, 2007). That is, this study does not
428 necessarily need to invoke a change in DOC availability up the soil profile as it
429 can also explain the observation based upon mixing of water sources, a low DOC
430 concentration end-member that represents rainwater and a high concentration
431 DOC end member that represents deep soil water. Evidence for this end-member
432 mixing interpretation comes from the fact that soil water conductivity is a

433 significant covariate for both soil water and surface runoff water DOC
434 concentrations with a positive correlation for each. Soil water that is high in DOC
435 would also be expected to have a high conductivity, conversely, rainwater has a
436 low conductivity and low DOC concentration. Therefore, this study would propose
437 that the declines in DOC concentration observed by this study are not due to
438 changes in production or the composition of the DOC rather it is due to changes
439 in hydrology that mean pathways higher in the peat profile come to dominate and
440 these have a lower available DOC concentration. This explanation of the
441 variation in the observed DOC concentrations does not require a difference in
442 DOC composition and indeed this study suggests that specific absorbance
443 follows the DOC concentration. However, the E4/E6 ratio does show significantly
444 lower values for burnt sites suggesting that there is a distinct effect due to
445 burning distinct from just vegetation cutting. Shifts in DOC composition would
446 have implications for the treatability of the streamwater (Sharp et al., 2008).

447 Does this hypothesis fit all the observations? Changes in DOC
448 composition are then controlled not by changes in production or solubility but
449 rather the mixing of two sources and the amount of DOC in the sample.
450 Differences between treatments can then be explained by differences in the
451 effect upon depth to the water table but why any one particular treatment affects
452 the depth to the water table in the manner it does is beyond the scope of this
453 study. However, one possible source of difference that this study cannot
454 presently assess is that water table and flowpaths in a particular treatment (eg.
455 cutting) are not just governed by the evapotranspiration from soil or plant

456 surfaces but also by the hydraulic conductivity and porosity of the soil. The
457 hydraulic conductivity of the peat profile at a particular dipwell may well be
458 governed by other physical features such as macropores and soil pipes (Holden
459 and Burt, 2003). Clay et al. (2009b) have measured soil hydraulic conductivities
460 between managed burnt and grazed sites and found variations of between $1.3 \times$
461 10^{-8} and 1.4×10^{-3} cm/s. Similarly, the porosity of the peat soil, as distinct from its
462 permeability of the peat, could be controlled by the particular management or
463 treatment of a study plot. Therefore differences in the depth to water table could
464 be highly influenced by existence of macropores in the peat that may not be
465 related to management on that site. The balance of flowpaths within and between
466 treatments will be the subject of future research. Further, no ANOVA performed
467 in the above analysis was successful in explaining 100% of the original variance
468 and indeed the error term is the most important term for all the DOC
469 concentration analyses. The error term represents all unexplained variance in the
470 original dataset and is not just the measurement or sampling errors but can
471 represent variation due any factors or interactions that were not or could not be
472 included in the analyses. An obvious factor that could not be controlled within this
473 study were the antecedent hydroclimatic conditions before sampling, i.e. the
474 study can account for seasonal cycles by sampling each month within a year but
475 it cannot account for a rain storm immediately before sampling. Furthermore, the
476 study could not include any sampling prior to management intervention, eg. prior
477 to burning or cutting. Therefore, it could be that the differences observed were
478 differences due to spatial variation across a peat-covered hillside. However, this

479 study was careful to ensure that plots were separated across a single
480 management type, that there is a minimum of six-fold replication within any
481 management type. Equally, the study has provided a consistent explanation of
482 the significant difference observed, i.e. mixing of water types as the depth to
483 water table changes upon management.

484 Can this proposed explanation account for other studies on the effect of
485 management intervention on DOC concentrations in and from peat soils? The
486 study here was on what normally be considered a dry peat, i.e. the control site
487 has an average water table depth of 44 cm while, for example, Evans et al.
488 (1999) showed that for another intact, UK upland peat soil the water table was
489 within 10 cm of the surface 80% of the year with the maximum summer water
490 table depth being 42 cm. The studies of Clay et al. (2009a and b) were
491 conducted on the same site as the study of Evans et al. (1999), i.e. a site far
492 wetter than one in the present study, and although differences between water
493 tables upon unburnt and burnt sites were significant the average difference was
494 the difference between 13 and 8.7 cm respectively. Therefore, we might propose
495 that the differences in DOC concentration observed by this study were due to
496 changes in the depth to the water table causing changes in source and mixing of
497 the soil water. Such an interpretation suggests that sites that are wetter prior to
498 intervention will see little effect as there are less dramatic changes in the water
499 table that can be achieved or that the baseline is already sufficiently high in the
500 profile that little difference can be made. Studies of drain-blocking have been
501 equivocal with regard to their effect upon DOC concentration – Wallage et al.

502 (2006) a decline; Worrall et al. (2007b) an increase; and Gibson et al. (2009) no
503 significant change - and this could be because some sites of drain blocking have
504 high water tables despite drainage and others do not.

505 This study was limited to considering soil water and surface runoff, it did
506 not consider stream water, therefore this study could not demonstrate that the
507 changes observed in this study would lead to decrease in DOC concentrations
508 experienced at a water supply intake in a catchment where cutting or burning had
509 been implemented. The stream water of a catchment will be a mixture of sources
510 within the profile and within the catchment. However, this study has shown that
511 soil water concentrations would decrease upon cutting, that although surface
512 runoff concentrations would not change surface runoff concentrations were
513 always lower than or equal to soil water concentrations and surface runoff
514 frequency increased with cutting. These facts suggest that stream water
515 concentrations would decline. However, if water tables rise under cut sites and
516 runoff frequencies increase it may mean that more water may leave the cut areas
517 than would have left the uncut areas. Thus in a catchment where there are a
518 range of soils this increase in water yield from the areas that produce the most
519 DOC (i.e. peat soils), even if that DOC concentration was lower than what it would
520 have been, could still produce an increase in DOC at a water treatment works
521 intake. However, Löfgren et al. (2010) when comparing plot scale measurements
522 with catchment scale measurements of DOC for sites undergoing recovery from
523 acidification, found that although there was a consistent response at the plot
524 scale to changing acidification there was not a consistent response at the

525 catchment scale. If this were true of management interventions like cutting then
526 the response at the catchment scale could be an increase, a decrease or no
527 change despite what is observed at the plot scale

528

529

CONCLUSIONS

530 The study has shown that both cutting and burning lead to declines in soil water
531 DOC concentration; and increases in surface runoff frequency. Although
532 management intervention brought about no significant differences in the DOC
533 concentration in the surface runoff water the combination of changes brought
534 about by cutting and/or burning will bring about a decline in DOC concentrations
535 in peat-covered catchments. The changes in DOC concentrations were explained
536 by changes in the depth to the water table and by the mixing of differing water
537 sources. Cutting and burning both act to lower DOC concentrations because they
538 cause the water table to rise from its relatively low position. The results of this
539 study could imply that both cutting and burning implemented in such a dry
540 context could have the same effect and reduce DOC concentrations in the
541 streamwaters of a catchment.

542

References

544 Aitkenhead, J.A., Hope, D., Billet, M.F., 1999. The relationship between dissolved
545 organic carbon in stream water and soil organic carbon pools at different
546 spatial scales. *Hydrological Processes* 13, 1289-1302.

547 Avery, B.W. 1980. Soil classification for England and Wales. Soil Survey of
548 England and Wales, Harpenden. Technical Monograph, 14, 67.

549 Bartlett, R. J., Ross, D.S., 1988. Colorimetric Determination of Oxidizable Carbon
550 in Acid Soil Solutions. Soil Science Society of America Journal 52(4), 1191-
551 1192.

552 Chapman P.J., Macdonald, A.T., Tyson, R., Palmer, S.H., Mitchell, G., Irvine B.
553 2010. Changes in water colour between 1986 and 2006 in the headwaters
554 of the River Nidd, Yorkshire, UK. Biogeochemistry 101, 1-3, 261-294..

555 Chapman, P.J., Palmer, S.M., Irvine B., Mitchell G., McDonald A., (2012). A
556 response to " Changes in water colour between 1986 and 2006 in the
557 headwaters of the River Nidd, Yorkshire, UK: a critique of the
558 methodological approaches and measurement of burning management" by
559 Yallop et al. Biogeochemistry (in press).

560 Chen, Y., Senesi, N., Schnitzer, M. (1977) Information provided on humic
561 substances by E4-E6. Soil Science Society of America Journal 41, 352-358.

562 Clay, G.D., Worrall, F., Fraser, E.D.G., 2009a. Effects of managed burning upon
563 dissolved organic carbon (DOC) in soil water and runoff water following a
564 managed burn of a UK blanket bog. Journal of Hydrology 367(1-2), 41-51.

565 Clay, G.D., Worrall, F., Fraser, E.D.G., 2009b. Hydrological responses to
566 managed burning and grazing in an upland blanket bog. Journal of
567 Hydrology 376, 486-495.

568 Clutterbuck, B. and Yallop, A.R., 2010. Land management as a factor controlling
569 dissolved organic carbon release from upland peat soils 2: Changes in DOC

570 productivity over four decades. *Science of the Total Environment*, 408(24):
571 6179-6191.

572 Dawson, J.J.C., Smith, P., 2007, Carbon losses from soil and its consequences
573 for land-use management. *Science of the Total Environment* 382, 165-190.

574 DEFRA 2007. The Heather and Grass Burning Code (2007 Version). DEFRA.

575 Driscoll, C. T., Driscoll, K.M., Roy, K.M., Mitchell, M.J., 2003. Chemical
576 Response of Lakes in the Adirondack Region of New York to Declines in
577 Acidic Deposition. *Environmental Science & Technology* 37,10, 2036-2042.

578 Evans, C.D., Monteith, D.T., Cooper, D.M., 2005. Long-term increases in surface
579 water dissolved organic carbon: observations, possible causes and
580 environmental impacts. *Environmental Pollution* 137, 55-71.

581 Evans, M.G., Burt, T.P., Holden, J., Adamson, J.K., 1999. Runoff generation and
582 water table fluctuations in blanket peat: evidence from UK data spanning
583 the dry summer of 1995. *Journal of Hydrology* 221, 141-160.

584 Freeman, C., Evans, C.D., Monteith, D.T., Reynolds, B., Fenner, N., 2001a.
585 Export of organic carbon from peat soils. *Nature* 412, 6849, 785-785.

586 Freeman, C., Fenner, N., Ostle, N.J., Kang, H., Dowrick, D.J., Reynolds, B.,
587 Lock, M.A., Sleep, D., Hughes, S., Hudson, J., 2004. Export of dissolved
588 organic carbon from peatlands under elevated carbon dioxide levels. *Nature*
589 430, 195-198.

590 Garnett, M.H., Ineson, P., Stevenson, A.C., 2000. Effects of burning and grazing
591 on carbon sequestration in a Pennine blanket bog, UK. *Holocene* 10, 729-
592 736.

593 Gibson, H.S., Worrall, F., Burt, T.P., Adamson, J.K., 2009. DOC budgets of
594 drained peat catchments – implications for DOC production in peat soils.
595 Hydrological Processes 23, 13, 1901-1911.

596 Harriman, R., Curtis, C., Edwards, A.C., 1998. An empirical approach for
597 assessing the relationship between nitrogen deposition and nitrate leaching
598 from upland catchments in the United Kingdom using runoff chemistry.
599 Water Air & Soil Pollution 105, 193-203.

600 Hejzlar, J., Dubrovsky, M., Buchtele, J., Ruzicka, M., 2003. The apparent and
601 potential effects of climate change on the inferred concentration of
602 dissolved organic matter in a temperate stream (the Malse River, South
603 Bohemia). The Science of Total Environment 310, 1-3, 143-152.

604 Helliwell, R.C., Britton, A.J., Gibbs, S., Fisher, J.M., Potts, J.M. 2010. Interaction
605 effects of N deposition, land management and weather patterns on soil
606 solution chemistry in a Scottish alpine heath. Ecosystems 13, 696-711.

607 Hobbs, R. J., 1984. Length of Burning Rotation and Community Composition in
608 High-Level Calluna-Eriophorum Bog in Northern England. Vegetatio 57, 2-3,
609 129-136.

610 Hobbs, R. J., Gimingham, C.H., 1984. Studies on Fire in Scottish Heathland
611 Communities .2. Post-Fire Vegetation Development. Journal of Ecology 72,
612 2, 585-610.

613 Holden, J., Burt, T.P., 2003. Hydraulic conductivity in upland blanket peat:
614 measurement and variability. Hydrological Processes 17, 6, 1227-1237 .

615 Hsu, C.H., Jeng, W.L., Chang, R.M., Chien, L.C., Han, R.C., 2001. Estimation of
616 potential lifetime cancer risks for trihalomethanes from consuming
617 chlorinated drinking water in Taiwan. *Environmental Research* 85, 2, 77-82.

618 Krug, E.C., Frink, C.R., 1983. Acid rain on acid soil: a new perspective. *Science*
619 211, 520-525.

620 Lance, A. N., 1983. Performance of Sheep on Unburned and Serially Burned
621 Blanket Bog in Western Ireland. *Journal of Applied Ecology* 20, 3, 767-775.

622 Lofts, S., Smith, B.M., Tipping, E., Woof, C. 2001. Modelling the solid-solution
623 partitioning of organic matter in European forest soils. *European Journal of*
624 *Soil Science* 52, 215-226.

625 Lofgren, S., Gustafsson, J.P., Bringmark, L. 2010. Decreasing DOC trends in soil
626 solution along the hillslopes at two IM sites in southern Sweden —
627 Geochemical modeling of organic matter solubility during acidification
628 recovery. *Science of The Total Environment* 409, 201-210.

629 Mallik, A.U., Gimingham, C.H., 1983. Regeneration of Heathland Plants
630 Following Burning. *Vegetatio* 53, 1, 45-58.

631 Mitchell, G., McDonald, A.T., 1995. Catchment characterisation as a tool for
632 upland water management. *Journal of Environmental Management* 44, 1,
633 83-95.

634 Picozzi, N., 1968. Grouse Bags in Relation to Management and Geology of
635 Heather Moors. *Journal of Applied Ecology* 5, 2, 483-488.

636 Sharp, E.L., Parson, S.A., Jefferson, B., 2006. Coagulation of NOM: linking
637 character to treatment. *Water Science and Technology* 53 (7), 67-76.

638 Skjelkvåle, B.L., Mannio, J., Wilander, A., Andersen, T., 2001. Recovery from
639 acidification of lakes in Finland, Norway and Sweden 1990-1999. *Hydrology*
640 & *Earth System Science* 5, 327-338.

641 Tallis, J.H., 1997. The pollen record of *Empetrum nigrum* in Southern Pennine
642 peats: Implications for erosion and climate change. *Journal of Ecology* 85,
643 4, 455-465.

644 Thurman, E.M., 1985, *Organic geochemistry of natural waters*. Nijhoff/Junk,
645 Dordrecht.

646 Tranvik, L.J., Jansson, M., 2002. Terrestrial export of organic carbon. *Nature*
647 415, 861-862.

648 Wallage, Z.E., Holden, J., McDonald, A.T., 2006. Drain blocking: An effective
649 treatment for reducing dissolved organic carbon loss and water
650 discolouration in a drained peatland. *The Science of the Total Environment*
651 367, 811-821.

652 Ward, S.E., Bardgett, R.D., McNamara, N.P., Adamson, J.K., Ostle, N.J., 2007.
653 Long-term consequences of grazing and burning on northern peatland
654 carbon dynamics. *Ecosystems* 10, 7, 1069-1083.

655 Winer, B.J., 1971. *Statistical principles in experimental design*. McGraw Hill, New
656 York.

657 Worrall, F., Adamson, J.K., 2008. The effect of burning and sheep grazing on soil
658 water composition in a blanket bog: evidence for soil structural changes?
659 *Hydrological Processes* 22, 2531-2541.

660 Worrall, F., Burt, T.P., 2004. Time series analysis of long term river DOC records.
661 Hydrological Processes 18, 893-911.

662 Worrall, F., Burt, T.P., 2007a. Trends in DOC concentration in Great Britain.
663 Journal of Hydrology 346, 3-4, 81-92.

664 Worrall, F., Burt, T.P., 2007b. Flux of dissolved organic carbon from U.K. rivers.
665 Global Biogeochemical Cycles 21, 1, art. no. GB1013.

666 Worrall, F., Armstrong, A., Adamson, J.K., 2007a. The effects of burning and
667 sheep-grazing on water table depth and soil water quality in an upland peat.
668 Journal of Hydrology 339, 1-2, 1-14.

669 Worrall F. Armstrong A. Holden J. 2007b. Short-term impact of peat drain-
670 blocking on water colour, dissolved organic carbon concentration, and water
671 table depth. Journal of Hydrology 337, 315-325

672 Yallop, A.R., Clutterbuck, B., 2009. Land management as a factor controlling
673 dissolved organic carbon release from upland peat soils 1: Spatial variation
674 in DOC productivity. The Science of the Total Environment 407, 12, 3803-
675 3813.

676 Yallop, A., Thacker, J., Clutterbuck, B., 2006. Mapping extent of burn
677 management in the North Pennines: Review of extent year 2001-2003.
678 English Nature Research Reports No 698, English Nature, Peterborough,
679 UK. Yallop, A.R., White, S.M. and Clutterbuck, B., 2008. Evidence for a
680 mechanism driving recent observed trends in dissolved organic carbon
681 release from upland peat soils. Aspects of Applied Biology, 85: 127-132,

682 Yallop, AR, Clutterbuck, B. Thacker, JI. (2012). Changes in water colour between
683 1986 and 2006 in the headwaters of the River Nidd, Yorkshire, UK: a
684 critique of the methodological approaches and measurement of burning
685 management. Biogeochemistry (in press).
686

1

2 *Table 1. The details of the site, treatment and number of samples taken for this*
3 *study.*

Site	Treatment	No. of samples
MOSS	New cut and lift	78
GS1	New cut and leave	78
BEN	Old cut and lift	36
GS3	Old cut and lift	39
OB	New burn	78
BN	Old burn (1 year)	36
BS	Old burn (1 year)	36
PROM	Old burn (5 year)	79
PAT	Control	78

4

5

6

1 *Table 2. The proportion of the original variance explained by each factor in the*
 2 *initial ANOVA. a) Comparison with all treatments; b) Comparison with treatment*
 3 *factor degraded to burning vs, cutting vs. control; c) Comparison of treatments*
 4 *including covariates; and d) Comparison between runoff and soil water*
 5 *concentrations.*

6 a)

	Soil water DOC	Water table	E4/E6	Spec. Abs.	Surface runoff DOC
Treatment	13	69	36	10	22
Month	39	7	15	10	12
Error	48	24	49	80	66

7

8 b)

	Soil water DOC	Water table	E4/E6	Spec. Abs.	Surface runoff DOC
Treatment	5	81	14	21	0
Month	61	7	34	19	0
Error	34	12	51	60	100

9

10 c)

	Soil water DOC	Spec. Abs.	Surface runoff DOC
Treatment	3	6	12
Month	28	14	7
Log(w ater table)	2	na	na
Log(cond)	2	23	8
pH			3
Error	65	58	70

11

12 d)

	DOC	Spec. Abs.	E4/E6
Treatment	14	1	2
Month	11	12	9
Type	10	0	7
Treat*type	0	0	7
Month*type	8	8	0
Error	57	79	75

13

1 *Table. 3. The proportion of surface runoff detected on each of the study sites.*

Treatment	Proportion of detection
New cut & leave	0.14
New cut & lift	0.27
Old cut & lift	0.38
New burn	0.14
Old burn (1 yr)	0.39
Old burn (5 yr)	0.1
Control	0.14

2

3

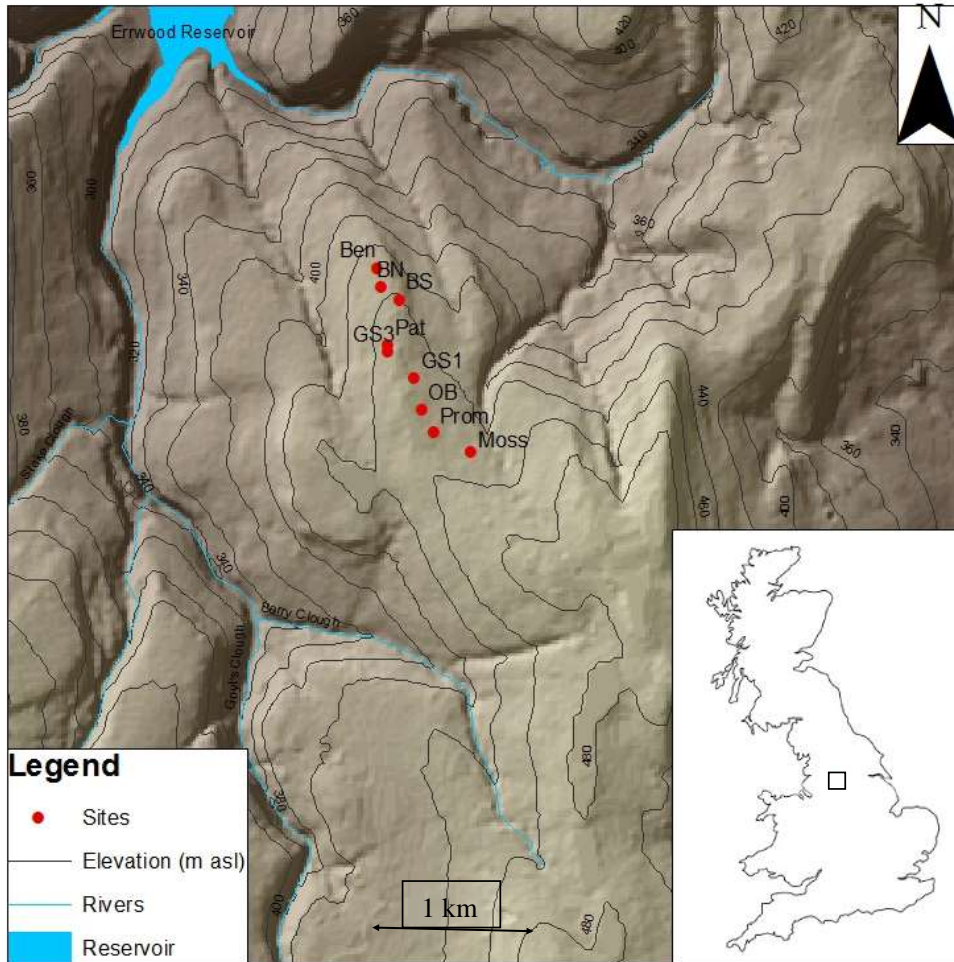
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6

1 Fig. 1. The location of the study sites used in this study– for codes refer to Table

2 1.



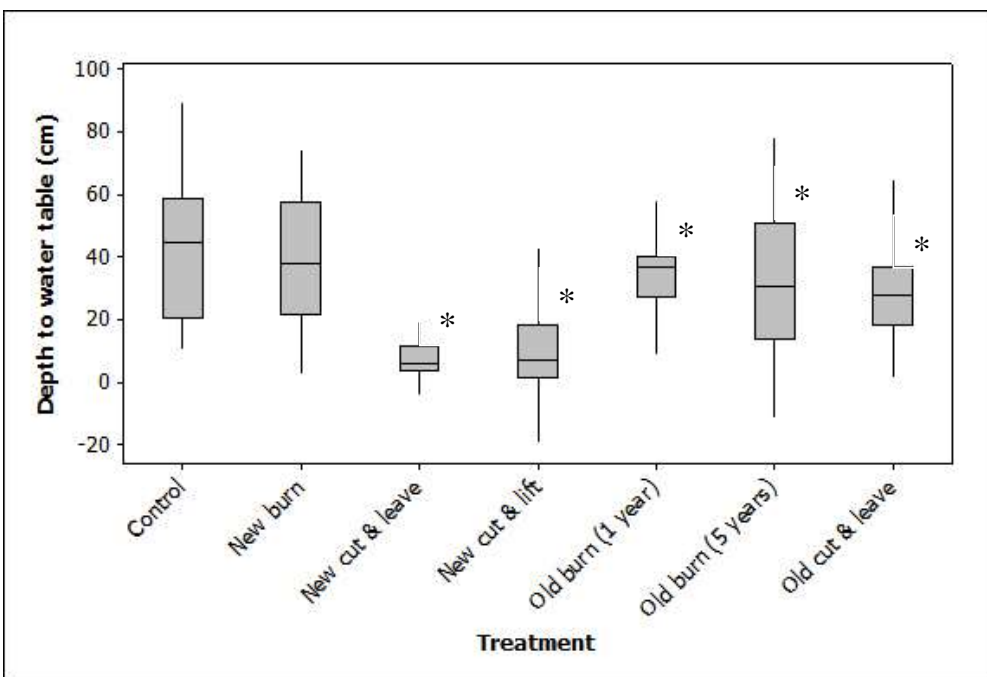
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1 Fig. 2. The box-whisker plot of the depth to water table across the treatments
2 across this study. The box represents the inter-quartile with a median line, the
3 whiskers represent the range of values. (*) indicates a treatment that is
4 significantly different from the control at the 95% probability.

5

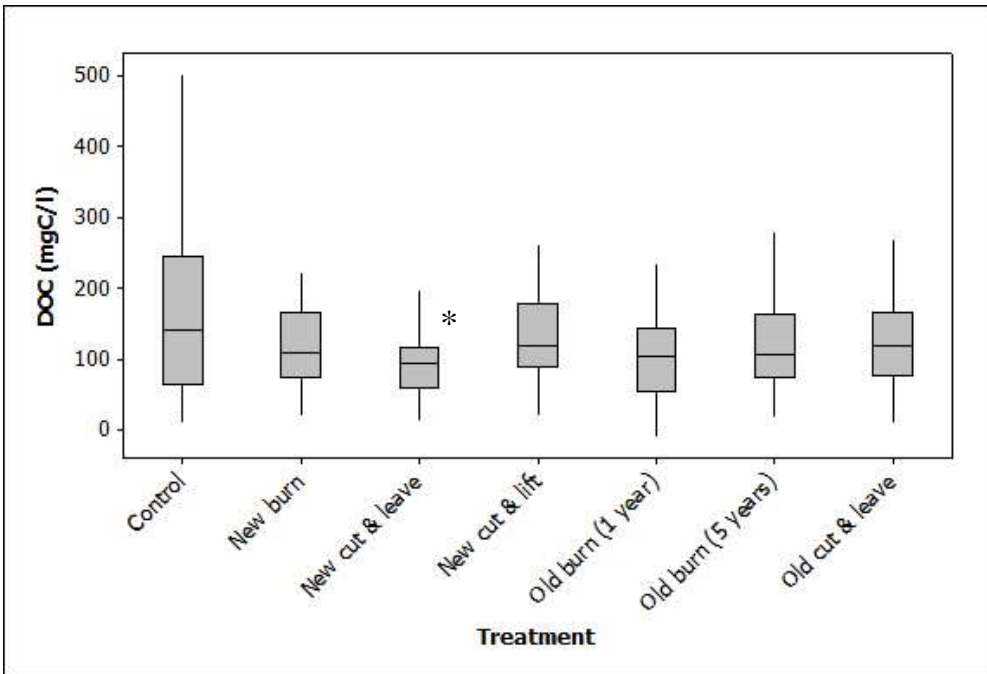


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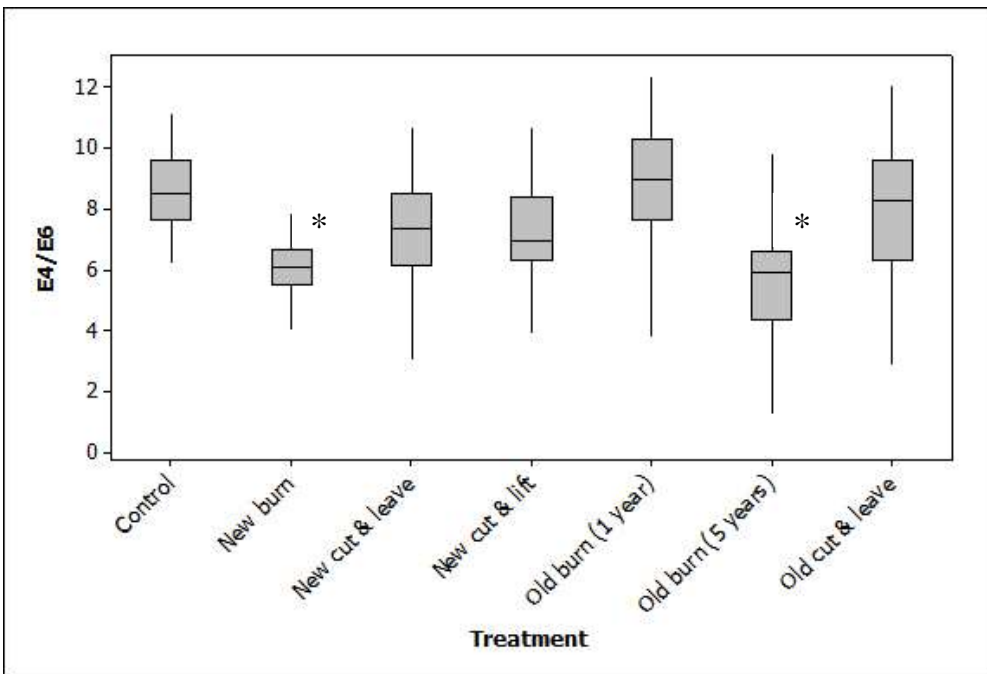
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1 Fig. 3. The box-whisker plot of the soil water DOC concentration across the
2 treatments across this study. The box represents the inter-quartile with a median
3 line, the whiskers represent the range of values. (*) indicates a treatment that is
4 significantly different from the control at the 95% probability.



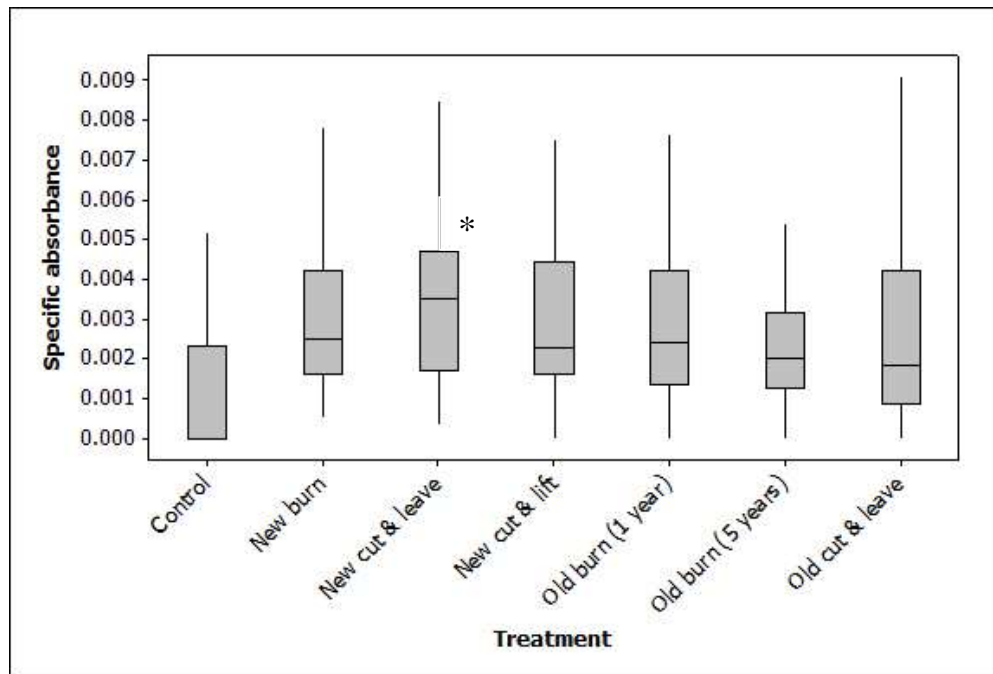
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1 Fig. 4. The box-whisker plot of the soil water E4/E6 across the treatments across
2 this study. The box represents the inter-quartile with a median line, the whiskers
3 represent the range of values. (*) indicates a treatment that is significantly
4 different from the control at the 95% probability.



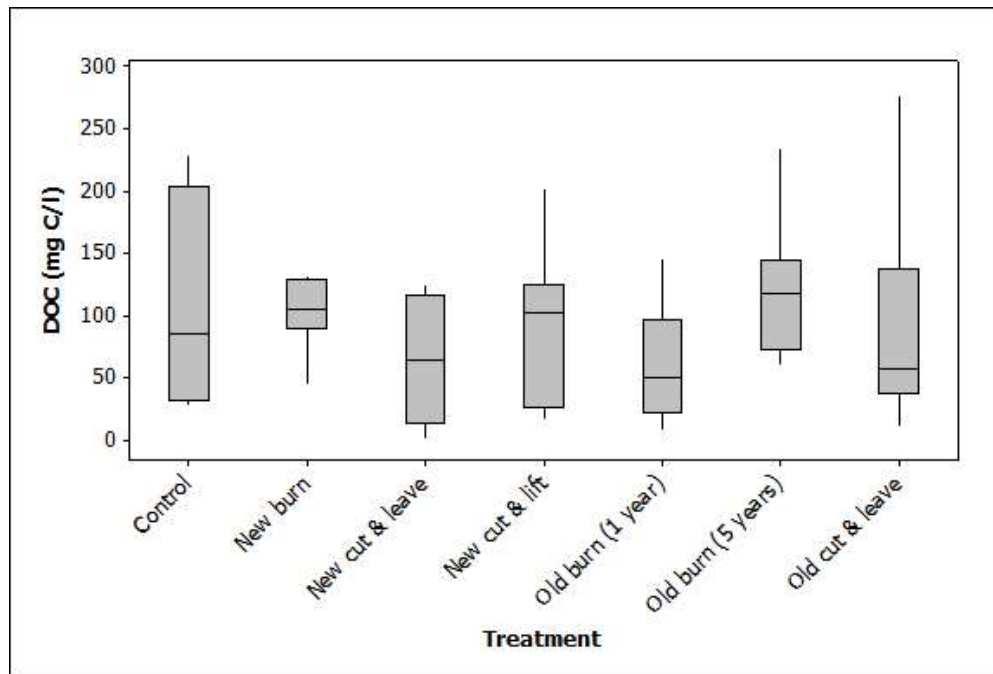
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1 Fig. 5. The box-whisker plot of the soil water specific absorbance across the
2 treatments across this study. The box represents the inter-quartile with a median
3 line, the whiskers represent the range of values. (*) indicates a treatment that is
4 significantly different from the control at the 95% probability.



5
6
7

1 Fig. 6. The box-whisker plot of the runoff water DOC concentration across the
2 treatments across this study. The box represents the inter-quartile with a median
3 line, the whiskers represent the range of values. No significant differences at the
4 95% probability were found between the control and any treatment.



5

